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BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

SUBJECT: A Study on Bulkhead Configurations for a Common Mission Module Case 103

DATE: January 9, 1969

FROM: C. C. Ong

ABSTRACT

A number of bulkhead configurations are evaluated for use as a substructure of the Common Mission Module. A brief survey on the bulkhead studies prepared by several aerospace companies is presented. These investigations have provided background for selection of the most promising configurations for a more refined weight analysis. Those which are selected include the elliptical-toroidal bulkhead and four versions of the flat bulkhead, namely, the honey-comb sandwich slab, the stiffened skin supported by interconnected beams, the stiffened skin supported by radial beams and the triangular sandwich panels supported by interconnected beams. The analytical results show that an elliptical-toroidal bulkhead possesses the highest weight saving potential followed by the triangular sandwich panel design and the radial beam design. However, a flat bulkhead is better than a curved one for other factors, such as equipment mounting, installation of docking ports, fabrication and handling. When meteoroid shielding for the additional module length of curved bulkhead designs is included, a flat bulkhead is also competitive weightwise.

When the bulkhead configurations are incorporated into the design of the CMM, it is found that a hybrid structure featuring one flat bulkhead and one elliptical-toroidal bulkhead is lightest.

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MEMORANDUM FOR FILE

I. INTRODUCTION

In current work at Bellcomm a basic building block identified as common mission module (CMM), has been proposed and studied.[1] Previous Bellcomm investigations indicated that a useful CMM size would be a cylindrical can, 15 to 22 feet in diameter. Bulkheads of various configurations can be incorporated into this cylindrical mission module and can have a significant influence on spacecraft weight.[2] Bulkhead configurations applicable to the design of space vehicles have also been widely studied by many aerospace companies either as a special research project[3] or as part of an advanced space vehicle study[4,5,6,7]. Due to the differences in their methods of analysis and materials used, it is difficult to draw a meaningful conclusion as to which of these investigated bulkhead configurations is most advantageous when applied to a CMM structure.

The purpose of this memorandum is to make comprehensive evaluations of the candidate bulkhead configurations by a uniform approach and to provide a guide for the design of CMM structures.

Presented in this study are the configurational concepts which have already been documented in the literature along with modified versions suggested by the author. A discussion of all of the prospects leads to the elimination of the least attractive ones and, furthermore, to the choice of five promising configurations for quantitative analysis. The weight-saving potential of each of the structural concepts are then estimated.

Various combinations of flat and elliptical-toroidal bulkheads are investigated for a mission module which requires a separate subsystem compartment in addition to a crew living cabin.

II GUIDELINES AND CONSTRAINTS

The following guidelines and constraints are assumed:

1. The basic CMM structure consists of a pressurized inner cylinder 240-inch in diameter and an unpressurized load-carrying cylinder of 260-inch in diameter. The inner pressure vessel is suspended within the load-carrying structure.

2. A central tube, 60-inch in diameter, extending along the entire length between the bulkheads of the pressurized structure, is required to serve both as a passageway/airlock and as a radiation shelter. The tube has a 36-inch diameter hatch at each end.

3. A safety factor of 2 is applied to the ultimate strength of the material in the analysis.

4. The bulkheads studies are made of 2014-T6 aluminum with the following properties:

   Ultimate Strength = 64,000 psi

   Modules of Elasticity = 10×10^6 psi

   Poisson's Ratio = 0.3

   Unit Weight = 0.1 lb/in^3

5. The requirements for windows, docking ports, and other penetrations are not considered in the weight estimates. Insulation and equipment mounting structures are also omitted.

III. INITIAL ASSESSMENT OF CANDIDATE CONCEPTS

Previous studies[2,3] indicate that weight saving may be achieved by designing a bulkhead with a low height-to-radius ratio. When the height of the bulkhead is reduced the length of the outer cylinder would also be reduced. A low profile bulkhead can be obtained without severe weight penalty either by replacing the conventional ellipsoidal membrane shell with a carefully designed flat structure, or by employing curved membranes restrained by rings, beams, webs, or tension members. Eleven bulkhead configurations applicable to a CMM structure are given in Figure 1. These configurations are grouped into two families according to their profiles. They are: (1) curved bulkheads, and (2) flat bulkheads. The first group includes the ellipsoidal bulkhead, the elliptical-toroidal bulkhead, the circumferential membranes with intermediate tension ties, the bubble-type membrane supported by radial beams, the shallow dome, and the scallop. The second group consists of the honeycomb sandwich slab bulkhead and five different versions of beam supported stiffened skin or beam supported honeycomb sandwich slab.

In the design of a CMM, the structural configuration must accommodate the requirements and limitations of all the probable missions. The significant design considerations include a high usable volume-to-weight ratio, an efficient structural interconnection with other modules of the spacecraft system, compatibility with environmental control, versatility in equipment mounting, ease of installing hatches or docking ports, free cabin space and, manufacturing feasibility.

In general, a flat bulkhead is favored over a curved bulkhead, because it permits full utilization of available cabin volume and offers a flat surface convenient for equipment mounting. Furthermore, it requires a relative simple procedure for fabrication or handling and is usually easy to adopt docking ports and other penetrations.

A curved bulkhead, on the other hand, does not possess such advantages due to its complex profile. The only possible advantage that the latter might have is in saving weight.

The weight saving potential of a specific configurations cannot be accurately assessed until detailed analyses on all the candidate configurations are performed and compared to one another. These analyses, usually involving a large amount of numerical work, are beyond the scope of this study. Therefore, only a brief conceptual evaluation of each configuration is presented in the following paragraphs. The intention is to eliminate some of the less desirable concepts and reduce the unnecessary effort in performing weight analysis.

A. Ellipsoidal Bulkhead (Fig. 1a-A)

The height-to-radius ratio of an ellipsoidal bulkhead is usually kept larger than $\frac{1}{\sqrt{2}}$, to avoid the compressive membrane stress at the shell equator. When this condition is satisfied ellipsoidal bulkheads offer a high volume-to-weight ratio. When a high-crown ellipsoidal bulkhead is applied to a CMM, the associated outer cylindrical wall will inevitably make the combined weight very high. On the other hand, if a low profile ellipsoidal configuration is used, a portion of the structure will be under compressive, circumferential membrane stress. The required weight of the bulkhead increases rapidly as the crown height reduces to a very small value whereas the weight (length) of the outer wall becomes smaller. Though an optimum crown height can be found through tradeoffs, The total weight of the CMM structure is still likely to be high[2]. This configuration would be attractive only if the space enclosed by the curved bulkheads could be fully utilized.

B. Elliptical-Toroidal Bulkhead (Fig. 1a-B)

This is an elliptical-toroidal shell membranes mated to the pressure shell cylinder and a central airlock tube. Similar to the ellipsoidal bulkhead, one of the problems encountered in this concept is that when the crown height reduces, the circumferential membrane stress near its outer edge may become compressive, thus requiring heavy strengthening in this portion of the structure in order to avoid instability failure.

However a previous Bellcomm study[2], based solely upon internal pressure loading indicated that this configuration can significantly reduce weight. For configurations with the same crown height, the toroidal bulkhead weight is about 24% to 35% lower than that of the ellipsoidal. This holds for a crown height ranging from 1.5 ft to 3.5 ft. and a central tube 48 inches in diameter. A similar concept was also recommended in reference 3 as a candidate configuration for the crew compartment design of a Mars-Venus Flyby spacecraft.

C. Circumferential Membranes (Fig. 1a-C)

This concept has its similarities to concept B. Its special feature is that in addition to an elliptical-toroidal shell membrane there is a central ellipsoidal dome proportioned in such a way that the crown height of the bulkhead can be kept very low without risking instability failure or inducing large weight penalty to the bulkhead shell structure. However, the design of such a pressurized container requires a stiffening ring at the junction of the semi-elliptical torus and the elliptical dome as well as a set of tension ties between the bulkheads. The tension ties are located some distance away from the central airlock shell wall. The net saving on overall structural weight is uncertain due to the addition of tension ties and the ring whereas the usable space within the cabin will be somewhat restricted. Therefore, this concept does not seem to offer great advantage over Concept B unless the ring and the tension ties are also required for other purposes such as equipment mounting.

D. Bubble-Type Membrane Supported by Radial Beams[3] (Fig. 1a-D)

This structure consists of a series of bubble-type membranes supported by radial beams. The profile is formed on the basis that a pressurized thin shell supported and restrained around its periphery will assume a bubble shape closely approximating a true membrane. Thus, a low height-to-radius ratio bulkhead can be obtained at the expense of additional radial beam weight.

The layout of this configuration offers some advantages over those previously described since installations of floor, radial partitions, and equipment mounting racks can be supported by the radial beams. But the volume enclosed by the bubbles themselves may be difficult to utilize.

It is felt that the complexity of the membrane profile will greatly increase the difficulty encountered in the fabricational process which might not be justified by merely moderate weight-savings.

E. Shallow Dome Bulkhead[3] (Fig. 1a-E)

This concept is similar to the ellipsoidal bulkhead with the exception that the meridional radius of the shell is constant throughout the bulkhead. This significantly simplifies the construction process. In order to construct a low profile bulkhead a large meridional radius is required. This requirement makes the thickness of the shell wall much larger than that of an ellipsoidal bulkhead. Furthermore, the high discontinuity stresses caused by the sharp angle at the junction between the shallow dome and the cylindrical wall necessitate some heavy reinforcement in the form of a stiffening ring. It is then clear that this configuration retains most of the disadvantages of a curved bulkhead, with little gain in weight saving as compared with a flat bulkhead.

F. Scallop Bulkhead[8] (Fig. 1a-F)

A scallop bulkhead is composed of partial truncated cones and spherical transition sections between the partial cones and the main body of the pressurized container. The associated main body is, in this case, a series of connected partial cylinders. A set of perforated webs which extend radially from the central airlock tube to the juncture of two cylindrical wall sections, and longitudinally between the junctures of the conical bulkhead sections are required. To assure uninterrupted usable cabin space, the openings in the webs must be made as large as possible. Hence the web structure is preferably in the form of a rigid frame.

This configuration promises a light bulkhead and a short CMM length. But these advantages would be offset by the added weight and inconvenience of the required web structure. Furthermore, when the thickness of the pressurized sidewall is determined to meet requirements of resisting the impacts of the meteoroids, the main body composed of partial cylindrical sections tends to be much heavier than required by pressure loading. Therefore, no substantial savings on the total CMM structural weight over other configurations (such as configuration B) can be expected. These considerations plus its complex geometric profile makes this configuration less attractive than the others.

G. Flat Honeycomb Sandwich[3,5] (Fig. 1b-G)

The honeycomb sandwich slab is a large flat panel with a high stiffness-to-weight ratio. The slab provides good insulation and good impact resistance. Furthermore, the pressure acting on the bulkhead can be transmitted uniformly to the cylindrical wall, thus making it unnecessary to have heavy stiffening structural members on the cylindrical wall to resist the highly concentrated load as those required in a bulkhead with radial beams. A honeycomb sandwich may not be the lightest weight flat bulkhead configuration; but it can be adapted with ease to the various cabin interior arrangements as well as to the additional hatches or other penetrations wherever needed. These advantages make this configurational concept outstanding and one which is worthy of serious consideration in the design of CMM bulkhead.

H. Stiffened Skin Supported by Radial Beams (Fig. 1b-H)

This flat bulkhead is composed of a thin skin with integral stiffeners which is supported by the radial beams. One set of the beam flanges can be machined integrally with the skin and the stiffeners from a thick aluminum plate. The beams are supported longitudinally at the central airlock tube and at the cylindrical sidewall. Radial beams may be used either inside or outside of the flat skin. Substantial weight savings can be achieved by applying a set of tension ties to provide intermediate support for the radial beams, when and if it is convenient to do so.

This bulkhead configuration is a very popular one. It has been widely adapted by the aerospace industries in their planning of advanced space stations[6,7].

I. Ring Stiffened Skin Supported by Radial Beams[4] (Fig. 1b-I)

This configuration is similar to concept H with different stiffeners. In this case, the stiffeners are rings arranged concentrically with the central airlock tube. The bulkhead skin is deflected into torispherical sections between stiffeners when subjected to pressurization. At all stiffener junctures the bulkhead skin should be preformed into the torispherical section to reduce discontinuity stresses.

While this configuration is more complex its weight is not much less than that of the configuration H.

J. Stiffened Skin Supported by Interconnected Beams[5] (Fig. 1b-J)

As shown in Fig. 1b, this bulkhead also bears resemblance to concept H. It differs from the latter primarily in two ways: (1) none of the beams are oriented in a radial direction and (2) some of the beams are continuous over the supports provided by the tension ties which are built integrally with the central airlock tube. These different arrangements offer an alternative version of the skin and beam configuration.

K. Triangular Sandwich Panels Supported by Interconnected Beams (Fig. 1b-K)

As shown in Fig. 1b, this bulkhead is a thin honeycomb sandwich slab supported by a set of interconnected beams. In this structure all of the beams, except four radially oriented ones, are continuous over the intermediate ties. Several tension ties are equally spaced along a circle outside the central airlock shell wall. The arrangement of the beams is such that all of them are either supported at the tension ties or connected to the outer cylindrical wall; consequently there will be no large concentrated load acting on any of the beams even if most of the beams are interconnected. The triangular panels of the sandwich slab are approximately the same size and maximum stresses in these panels are therefore nearly uniform.

This configuration should have a great weight saving potential. In addition, the special pattern of the beam arrangement permits the airlock tube to be moved to an eccentric position close to the sidewall, if desired, without making sacrifice in weight saving.

The intermediate tension ties are an undesirable feature in this concept since they might obstruct usable cabin space. However, if the space immediately outside of the central airlock, which also serve as radiation shelter, is to be used for stocking food and other consumables; then, it is conceivable that the tension ties can be used conveniently as part of the storage structure.

IV. BULKHEAD STUDIES BY AEROSPACE COMPANIES

It is clear from the discussions given in the last section that, while some of the configurational concepts show more advantages than others, there is no one that appears to be superior in all aspects. Therefore, a brief survey of studies prepared by several aerospace companies will be helpful in clarifying the special characteristics of the individual bulkhead and, furthermore, in narrowing down the choice to a few outstanding ones for a more thorough weight analysis.

A. NAA Studies

The Space and Information Division of North American Aviation, Inc. completed a comprehensive study[3] in 1966 on various bulkhead configurations. Fourteen bulkhead concepts described in this study were applicable to a launch vehicle structure, and five configurations were evaluated for applicability to a multi-floor mission module of a Mars-Venus Flyby System. These five bulkhead configurations, as shown in Fig. 2, are the flat honeycomb, the ellipsoidal bulkehad, the modified semi-toroidal bulkhead, the shallow dome bulkhead as well as the membranes supported by the radial beams. The estimated weights of these bulkheads are listed in Table 1. In the original NAA report the data given were the required weights of the bulkhead itself. In order to make these data consistent with CMM design weight of the associated outer wall (calculated on the basis of 3 lb/ft^2) is added and the total weight is given in the last row of Table 1.

It can be seen that the modified semi-toroidal bulkhead is the lightest while the flat honeycomb is second.

The NAA bulkhead study concluded with the following sentences:

> "The study has shown that modified semi-toroidal bulkhead concept can be applied to advantage in crew compartment of advanced spacecraft. When incorporated in the design of the manned module of a Mars-Venus Flyby System, this concept led to a design with maximum usable volume at minimum weight increase, as compared with the spherical module studied by NASA/MSFC and cylindrical module with other bulkhead geometries. Furthermore, the mission module design with the modified semi-toroidal bulkhead is easily integrated with the launch vehicle and the other spacecraft modules, and is compatible with incorporation of docking provisions, airlock, radiation "storm cellar," and an internal centrifuge."

However, in the final Report of "The Study of Manned Planetary Flyby Missions Based on Saturn/Apollo Systems"[4] flat bulkheads were recommended for the crew compartment of the Mars-Venus flyby spacecraft. The reasons given for this change are that the flat bulkhead provides a full utilization of the available cabin volume and offers a flat surface for mounting equipment and contents of the module.

Two types of constructional concepts were investigated for the flat bulkhead design; they are (1) aluminum honeycomb and (2) ring-stiffened skin supported by radial beams. These concepts are identical with concepts G and I, respectively, as shown in Fig. 1b and are discussed in the last section of this memorandum. A parametric analysis of bulkhead weight optimation for the Radial Beam configuration resulted in a unit weight of about 3.0 lb/ft^2 for a 260-inch diameter module with a 3 ft diameter tunnel at the center. The ring-stiffened radial beam bulkhead was recommended because the design offers hard points at the rings and the beams for equipment mounting as well as easy repair of structural damage.

B. Lockheed Study

In the "Modular Multipurpose Space Station Study"[5], by the Lockheed Co., two versions of the one-compartment laboratory module were designed, one with a honeycomb flat bulkhead and one with an integral beam bulkhead. The integral beam configuration is similar to concept J of Fig. 1b. In the final version of the laboratory module, the integral beam bulkhead was adopted because the beam design was lighter. A breakdown of the estimated bulkhead weight for a 183-in diameter module is given in Table 2.

C. Boeing Study

In the Boeing "Saturn V Single Launch Space Station and Observatory Facility Study"[6], flat bulkheads were selected for a 33 ft diameter station with a 15 ft diameter core module. The bulkhead configuration selected is similar to the concept H of Fig. 1b.

The Boeing report mentioned that during the study several bulkhead shapes and stiffening methods were investigated. Spherical bulkheads were compared to elliptical and flat bulkheads. The weight differentials, including skirt weights, were found to be rather small if the flat bulkheads were reinforced with tension ties. In reality, the weight per unit of usable volume was found to be less for flat bulkheads than for spherical bulkheads.

V. ANALYSIS AND WEIGHT ESTIMATES OF SELECTED CONFIGURATIONS

A brief conclusion can be drawn from the discussions presented in the two previous sections that the elliptical-toroidal bulkhead stands out as the most attractive candidate among the curved bulkhead configurations primarily due to its weight saving potential. The flat bulkhead configuration is favored in so far as the geometric factor is concerned. However, the relative weight-saving potentials of the various flat bulkhead concepts are not readily seen.

Five configurational candidates, including the elliptical-toroidal bulkhead and four versions of flat bulkheads, were selected for a more detailed analysis as well as for weight estimation. These five configurations correspond to concept B, G, H, J and K which have been discussed in the previous sections.

Obviously, a large number of different materials can be applied to a bulkhead structure and various methods can be used for the analysis. With this in mind, an effort has been made to provide a consistent set of weight estimates. The structural material for all the bulkheads is 2014-T6 aluminum, whose specification is given in Section 2 of this memorandum, and the unit weight of the CMM outer wall is assumed to be 3 lbs/ft^2.

Pertinent equations, the assumed load distributions on the members of the bulkhead structure and some of the key techniques used in the analyses are given in the Appendix of this memorandum.

A brief discussion of the highlights of the analysis, the design features, and the estimated weights for each of the five selected bulkhead configurations are presented in the following paragraphs.

A. Elliptical-Toroidal Bulkhead (Concept B)

The method of analysis used on this structure is similar to that given by Reference 2. Weight is estimated under the assumption that the bulkhead is a monocque shell structure; and the thickness of the shell in the region under circumferential compression is governed by buckling criterion given in the Appendix.

The total structural weight of the bulkhead and the associated outer wall depends upon the crown height of the semi-elliptical toroid. With an outer wall weight of 3 lbs/ft^2 the total weight minimizes with a crown height of 38 inches. A breakdown of this estimated minimum weight is given as follows:

Semi-elliptical Toroid	175 lbs
Ring (at central airlock)	30 lbs
Central plate and hatch	50 lbs
Outer Wall	645 lbs
TOTAL	900 lbs

It should be noted that the shell membrane has a minimum thickness of 0.022 in. Should any engineering considerations other than the internal pressure requires a higher value of minimum thickness, the weight of the structure would be increased accordingly.

B. Honeycomb Sandwich Slab (Concept G)

The analysis of a honeycomb sandwich slab is performed on the basis that the circular slab with a central circular hole 60 inch in diameter is simply supported on both edges and loaded uniformly over the entire surface.

The sandwich slab is 6 1/2 inch deep and the face sheets have a thickness of 0.030 in. The estimated weights of the slab and its associated structures are:

Facings	254 lbs
Honeycomb Core	708 lbs
Adhesive	58 lbs
Tolerance (Inserts, Edgings, etc.)	50 lbs
Hatch	25 lbs
Rings	42 lbs
Outer Wall	83 lbs
TOTAL	1220 lbs

It should be mentioned that the total weight given above does not include that of any heavy insert or reinforcement which might be needed for equipment mounting.

C. Stiffened Skin Supported by Interconnected Beams (Concept J)

The methods applied to analyze this configuration are similar to those used in the Lockheed Study[5].

The bulkhead is composed of a skin 0.042 in. thick with integrally built stiffeners, spaced 4 inches apart and a set of interconnected built-up beams. The heaviest beams are 8 inches in depth. Four posts, tieing the bulkheads together near the center, are built integrally into the airlock tube. The beams terminated at the main pressurized cylindrical wall are assumed to be pin-supported by a one-piece machined ring with a channel cross section.

The weights of the bulkhead and its associated structures are estimated as:

Skin	190 lbs
Stiffeners	160 lbs
Beams	528 lbs
Ring	83 lbs
Hatch	25 lbs
Joints, Splices, Tolerances, etc.	50 lbs
Posts	22 lbs
Outer wall	102 lbs
TOTAL	1160 lbs

D. Stiffened Skin Supported by Radial Beams (Concept H)

This bulkhead also has a skin thickness of 0.042 in. and a maximum stiffener spacing of 4 in.; all the radial beams are 7 in. deep and assumed to be pin-supported by the rings at the cylindrical wall and at the airlock tube. Estimated weights are:

Skin	182 lbs
Stiffeners	200 lbs
Radial Beams	400 lbs
Rings	104 lbs
Hatch	25 lbs
Joints, Splices, Tolerances, etc.	50 lbs
Outer wall	89 lbs
TOTAL	1050 lbs

E. Triangular Sandwich Panels Supported by Interconnected Beams (Concept K)

The triangular-shaped sandwich panels, continuous over the supports, are analyzed under the assumption that it is an isosceles right triangle simply supported along the edges. In this analysis, the effect of beam deflection is ignored for it is considered to be offset by the effects of the continuity over the supporting edges.

The sandwich plate is 1 in. thick and the maximum depth of the beams is 5 in.. It has been noted in the course of analysis that a simple load distribution, with each beam carrying an applied cabin pressure midway to the adjacent beams, would give approximately the same loading conditions as those obtained by a more elaborated application of plate theory. This fact can be seen from the loading diagrams shown in Figure A-12 to Figure A-14

The estimated weights are given as follows:

Honeycomb Sandwich Slab	320 lbs
Beams	415 lbs
Ring	84 lbs
Tension ties	26 lbs
Hatch	25 lbs
Inserts, Fasteners, etc.	50 lbs
Outer wall	64 lbs
TOTAL	985 lbs

The results of the weight estimates for the five selected bulkhead configurations are summarized in Table 3.

CONCEPT	CONFIGURATION	WEIGHT OF BULKHEAD AND ASSOCIATED OUTER WALL (IN LBS)
B	Elliptical-Toroidal Bulkhead	900
G	Honeycomb Sandwich Slab	1,220
J	Stiffened Skin Supported by Interconnected Beams	1,160
H	Stiffened Skin Supported by Radial Beams	1,050
K	Triangular Sandwich Panels Supported by Interconnected Beams	985

TABLE 3. Bulkhead Weight Estimates

It can be seen that the maximum difference in weight among the five configurations studied is 320 lbs, or about 35% of the smallest value. The elliptical-toroidal bulkhead allows the smallest total weight but when it is compared with the triangular sandwich panels or the radial beam flat bulkhead, the amount of weight saved is only moderate. The triangular sandwich panels is the second lightest one, yet it requires the use of tension ties which may not be desirable.

VI. CMM APPLICATION

Many combinations of bulkheads can be incorporated into the design of the CMM structure. It is the purpose of this section to show influence of bulkhead configuration on the total weight of a CMM structure.

In addition to the general guidelines and constraints stated in Section II of this memorandum, it is further assumed that two separate, pressurized compartments are required in the CMM structure. The main compartment has a minimum headroom of 6 1/2 ft and is pressurized with GO_2 + GN_2 atmospheres at 7 psi. A smaller compartment within which the atmosphere is GN_2 at 7 psi, shall provide space needed for housing subsystems. Furthermore, the CMM has an unpressurized section large enough to store cryogenic tanks with a maximum diameter of 3 1/2 ft.

Four different CMM configurations are formulated as shown in Figure 3 and the estimated structural weights are related in Table 4. The structural weights listed in this table are estimated based on an unpressurized outer wall weight of 3 lbs/ft^2.

In the following, a brief description is given on the general layout of these four CMM configurations:

<u>Configuration I</u>: Elliptical-toroidal bulkheads are used in this configuration. The ceiling and the floor are constructed of skin and beam type of structure. The space between the upper bulkhead and ceiling are sealed to form a subsystem compartment. Several hatches will be installed on the ceiling; and the cryogenic tanks are supported by the outer cylindrical wall. The entire pressurized container is suspended from a field-joint ring of the outer cylinder.

<u>Configuration II</u>: Radial-beam flat bulkheads are applied in this configuration. The subsystem compartment and the

main compartment are separated by a flat ceiling similar in construction to that of configuration I. Subsystems can be tied to the upper bulkhead which also support the cryogenic tanks located outside of the pressurized container. In general, bulkhead of radial beams construction is recommended over a honeycomb sandwich structure not only because of its weight saving potential but also because it provides better equipment mounting supports. Furthermore, it assures easy detection and repair of any structural damage

Configuration III: This configuration is a hybrid being composed of a combination of a flat bulkhead and an elliptical-toroidal bulkhead. The upper flat bulkhead of radial beam construction provides easy support for tankage as well as pick up points for the suspension of the pressurized container. The compartment adjacent to the lower curved bulkhead can be used to house the subsystems; and the partition floor can provide structural support for equipments housed in both the main compartment and the subsystem compartment.

Configuration IV: This structure is similar to configuration I. In this case, the ceiling is eliminated, thereby shortening the overall length of the CMM. The space below the flat floor is used as subsystem compartment as in configuration III. Due to lack of rigidity of the pressurized inner structure, it is necessary in this configuration to use extra tension ties during launch as shown by the dotted lines in Figure 3b.

It is shown in Table 4 that configuration IV offers a structure which is the lightest in weight when the outer wall has a unit weight of 3 lbs/ft^2. The structure defined by configuration III is slightly heavier, and configuration II is the heaviest of all. Nevertheless, the differences among the four configurations are all less than 10% of the lightest one.

When the outer wall weight is increased, configuration IV becomes heavier than configuration II and III. For an outer wall weight ranging from 5 to 11 lbs/ft^2 configuration III gives the lightest structure. If the weight of the outer wall further increases, configuration II becomes lightest as can be seen in figure 4.

It is noted that, in applying configuration IV, there is a substantial weight penalty for additional supporting structures associated with the cryogenic tanks which in this case are necessarily tied to the outer wall. Furthermore, structure needed for mounting equipment inside of the main compartment may prove costly in the actual construction of the CMM structure. On the other hand, configuration III possesses most of the prominent features of a flat bulkhead configuration.

Conclusion

It is therefore concluded that for a CMM with moderate outer wall weight (less than 10 lbs/ft^2) the hybrid configuration III is a promising one and for a CMM with a very heavy outer wall the flat bulkhead configuration II is definitely the best choice.

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Attachments
- References
- Appendix
- Figures

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APPENDIX

BULKHEAD STRUCTURE ANALYSIS

The key equations and load distributions as well as the primary steps used for stress analysis of the bulkhead structures are summarized as follows:

1. Elliptical-Toroidal Bulkhead (Fig. A-1)

A detailed analysis of this shell structure can be found in Reference 2. The meridional force, N_ϕ^{hd} and the circumferential membrane force, N_ϕ^{hd} are defined as

$$N_\phi^{hd} = \frac{p(r_0^2 - f^2)}{2r_0 \sin\phi} \qquad (1.1)$$

$$N_\theta^{hd} = \frac{p}{2r_1}\left[r_3^2 - 2(r_3 \sin\phi + f)\,\frac{(a^2 - b^2)\sin\phi}{a^4}\, r_3^3\right] \qquad (1.2)$$

or

$$N_\phi^{hd} = \frac{p(x + 2f)}{2(x + f)}\,\frac{(a^4y^2 + b^4x^2)^{\frac{1}{2}}}{a^4} \qquad (1.3)$$

$$N_\theta^{hd} = \frac{p(x + f)(a^4y^2 + b^4x^2)^{\frac{1}{2}}}{b^2x}\left[1 - \frac{(x + 2f)a^4b^2}{2(x + f)(a^4y^2 + b^4x^2)}\right] \qquad (1.4)$$

The maximum stress near the joint between the bulkhead and the airlock tube is

$$(\sigma)^{hd}_{S_{max}} = \frac{(N_\phi)^{hd}_s}{h} + \frac{C\beta^2D}{Eh}\left[(N_\theta)^{hd}_s - (N_\theta)^{cy}_s\right]e^{-\frac{\pi}{4}}\sin\frac{\pi}{4} \qquad (1.5)$$

where

$$\beta = \frac{3(1-\nu^2)}{a^2h^2} \qquad D = \frac{Eh^3}{12(1-\nu^2)}$$

p = Internal pressure

x,y = Cartesian coordinates of an arbitrary point

ϕ, θ = Spherical coordinates of an arbitrary point

$(N_\theta)_S^{hd}$ and $(N_\theta)_S^{cy}$ are the circumferential membrane force in the bulkhead and in the airlock cylinder at the junction S, respectively. In the region where the circumferential force becomes compression, the possibility of buckling is examined by the relation

$$\sigma_{cr} = \frac{E}{\sqrt{3(1-\nu^2)}} \frac{h}{\gamma} \tag{1.6}$$

where

h = wall thickness

$$r = \frac{1}{2}\left(\frac{b^2}{a} + \frac{a^2}{b}\right) \tag{1.7}$$

2. Honeycomb Sandwich Slab (Fig. A-2)

In a circular flat plate with a concentric circular hole and simple supports at both edges, the maximum moment in the radial direction and the shearing forces at the edges, induced by a uniform transverse load p over the entire plate, can be expressed as[9]:

$$M_{max} = \frac{1}{6} \beta p a^2 \tag{2.1}$$

$$\tau = kpa \tag{2.2}$$

where

h = thickness of the plate

when $\frac{a}{b} = 4$

We have

$\beta = 0.3666$

k (at outer edge) = 0.2866

k (at inner edge) = 0.7297

The stresses in a honeycomb sandwich slab (Fig. A-3) under a bending moment M and a shear force τ as given by Eqs (2.1) and (2.2) are[10]

Maximum Facing Stress

$$\sigma_f = \frac{M}{t_c t_f} = \frac{1}{6} \frac{\beta p a^2}{t_c t_f} \tag{2.3}$$

Core Shear

$$\tau_c = \frac{2\tau}{t + t_c} = \frac{kpa}{t + t_c} \tag{2.4}$$

3. Stiffened Skin Supported by Interconnected Beams (Fig. A-4)

The skin panels with maximum width of 4 in. between the stiffeners are analyzed as fixed ended beams. The T-shaped integral stiffness as well as beams 1, 2 and 3 are also assumed to be fixed ended with loadings as shown in Fig. A-5. Beam 4 is simply supported and its mode of loading is shown in Fig. A-6. Beam 5, 7 inch in depth, is assumed to be also simply supported at the outer ends yet continuous over the intermediate supports. The moments at these intermediate supports under the loading shown in Fig. A-7 can be calculated by the theory of three moments as:

$$M_A L_1 + 2M_B(L_1 + L_2) + M_c L_2 = -\frac{6A_1 x_1}{L_1} - \frac{6A_2 x_2}{L_2} \quad (3.1)$$

$$M_B = M_c = \frac{1}{2L_1 + 3L_2}\left(\frac{w_1 L_1^3}{4} + \frac{7w_2 L_1^2}{30} + \frac{w_3 L_2^3}{4}\right) \quad (3.2)$$

4. Stiffened Skin Supported by Radial Beams (Fig. A-8)

The skin panels and the stiffeners between the beams are analyzed as fixed ended beams with the size of the stiffener varied according to its length. The loading on the simply supported radial beams is given by Fig. A-9 and these beams are 7 inches in depth

5. Triangular Sandwich Panels Supported by Interconnected Beams (Fig. A-10)

When a simply supported isosceles right triangular plate is under transverse uniform load p as shown in Fig. A-11, the maximum moment is[9]

$$M_{max} = 0.0215\ pa^2 \quad (5.1)$$

The deflection of the plate can be expressed as[11]:

$$\omega = \frac{16pa^4}{\pi^6 D}\left[\sum_{m=1,3,5}^{\infty}\ \sum_{n=2,4,6}^{\infty} \frac{n\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{a}}{m\left(n^2-m^2\right)\left(m^2+n^2\right)^2} + \sum_{m=2,4,6}^{\infty}\ \sum_{n=1,3,5}^{\infty} \frac{m\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{a}}{n\left(m^2-n^2\right)\left(m^2+n^2\right)^2}\right] \quad (5.2)$$

where

$$D = \frac{Eh^3}{12(1-\nu^2)}$$

is the flexural rigidity of the plate. The reactional forces distributed along the edges AB and AC can be expressed as

$$\left(V_x\right)_{y=0} = \left(V_y\right)_{x=0} = \left(Q_x - \frac{\partial M_{xy}}{\partial y}\right)_{y=0} \tag{5.3}$$

and the concentrated reaction at corner A is

$$R_A = 2\left(M_{xy}\right)_{x=0,y=0} \tag{5.4}$$

where

$$M_{xy} = D(1-\nu)\frac{\partial^2 \omega}{\partial x \partial y} \tag{5.5}$$

$$Q_x = -D\frac{\partial}{\partial x}\left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2}\right) \tag{5.6}$$

The reactional forces along the edge BC can be obtained by substituting the following relations into Eq. (5.2)

$$\begin{aligned} x &= x_1\cos\alpha - y_1\sin\alpha = \frac{\sqrt{2}}{2}(x_1-y_1) \\ y &= x_1\sin\alpha + y_1\cos\alpha = \frac{\sqrt{2}}{2}(x_1+y_1) \end{aligned} \tag{5.7}$$

Then we have

$$Q_{x_1} = -D\frac{\partial}{\partial x_1}\left(\frac{\partial^2 \omega}{\partial x_1^2} + \frac{\partial^2 \omega}{\partial y_1^2}\right) \tag{5.8}$$

$$M_{x_1y_1} = D(1-\nu)\,\frac{\partial^2\omega}{\partial x_1 \partial y_1} \tag{5.9}$$

The reactional forces are, therefore,

$$\left(V_{x_1}\right)_{x_1=\frac{a}{\sqrt{2}}} = \left(Q_{x_1} - \frac{\partial M_{x_1y_1}}{\partial y_1}\right)_{x_1=\frac{a}{\sqrt{2}}} \tag{5.10}$$

$$R_c = R_B = \left(M_{xy}\right)_{x=0,y=a} + \left(M_{x_1y_1}\right)_{x_1=\frac{a}{\sqrt{2}},\ y_1=\frac{a}{\sqrt{2}}} \tag{5.11}$$

After the maximum moment and maximum shearing forces are obtained, the design of the sandwich panels can be executed by applying Eqs. (2.3)

The loadings applied in the analyses of the beams are shown in solid lines of Figs. A-12 to A-14. These simplified loading conditions were obtained by assuming that the pressure acting on the plate panels are reacted by the beams according to the load distribution pattern given by the dotted lines of Fig. A-10. If the reactions of the panels were calculated by applying the plate theory as given by Egs. (5.3), (5.4) and (5.10), the loadings on the beams would be those given by the dotted lines in the diagrams. The theory of three moments are then applied to obtain the moments over the intermediate supports of the continuous beams similar to that described previously in connection with Eq. (3.1).

(1) FLAT HONEYCOMB BULKHEAD		(2) ELLIPTICAL BULKHEAD		(3) MODIFIED SEMI-TOROIDAL BULKHEAD		(4) SHALLOW DOME BULKHEAD		(5) MEMBRANES SUPPORTED BY RADIAL BEAMS BULKHEAD	
Component	Weight (in lbs)	Component	Weight (in lbs)	Component	Weight (in lbs)	Component	Weight (in lbs)	Component	Weight (in lbs)
Face Sheets	446	Skin	326	Toroidal Skin	298	Skin	690	Skin	304
Core	222	Manhole	150	Center Panel	59	Edge Ring	285	Beams	128
Edge Ring	327			Manhole	150	Manhole	150	Sidewall Fittings	12
Manhole	150							Rings	130
								Manhole	150
TOTAL	1145		476		507		1125		724
OUTER WALL	35		1510		585		104		525
TOTAL (Including OUTER Wall)	1180		1980		1092		1229		1249

Note: (1) The estimates are performed on the base of an internal cabin pressure of 7.0 psia. A safety factor 1.5 is applied to the ultimate material strength of 65,000 psi.

(2) The outer wall is assumed to have a unit weight of 3 lbs/ft^2.

(3) The MM pressure vessel has a diameter of 260-in, with a central tube 60-in in diameter.

TABLE 1: Bulkhead Weight Estimates Prepared by NAA

ITEM	HONEYCOMB SANDWICH 4.0-INCH DEPTH		BEAM SUPPORTED INTEGRALLY STIFFENED SKIN	
	UNIT DETAIL	Weight (LB)	UNIT DETAIL	WEIGHT (LB)
Pressure Skin	.05 Al 2 required	258	.04 Al 1 required	104
Honeycomb Core	4.2 lb/ft^3 6.25 lb/ft^3	230 26		
Foam Attach Rings & Cross Members	17.0 lb/ft^3 @ 3/8" thick	18		
Adhesive	.1 lb/ft^2/ face	35		
Beams				234
Stiffeners				72
Radial Skin & Attach Provision		14		20
Floor Interconnect Provision	Fiber Glass	15	Al Poles	17
Tolerances, Fillets etc.	10%	59	15%	70
TOTAL (not including Docking Ring		653		517

NOTE: (1) A safety factor 2 is applied to the ultimate strength of the materials.

(2) Ultimate Strength of the materials: Integral floor - 85,000 psi
lower flange of the beams - 75,000 psi

TABLE 2 Weight Estimates For A 183-in. Diameter Laboratory Module Prepared By Lockheed

ITEMS	CONFIGURATION I	CONFIGURATION II	CONFIGURATION III	CONFIGURATION IV
Outer Cylinder (3 lbs/ft^2)	3,360	2,700	2,870	3,110
Pressurized Cylinder	315	430	330	260
Reinforcement at skirt for Meteroid Protect	230		95	255
Ceiling	450	200		
Floor	450		450	500
Central Airlock (including Hatches at ends)	290	355	295	405
Pressure Shell Support	100	100	100	260
Field Joint Rings	485	485	485	485
Elliptical-Toroidal Bulkhead	350		175	350
Radial Beam Bulkhead		1,870	935	
SUB TOTAL	6,030	6,140	5,735	5,610
Contingency 10%	605	615	575	560
TOTAL	6,635	6,755	6,310	6,170

TABLE 4 CMM Structural Weight Trend (in lbs)

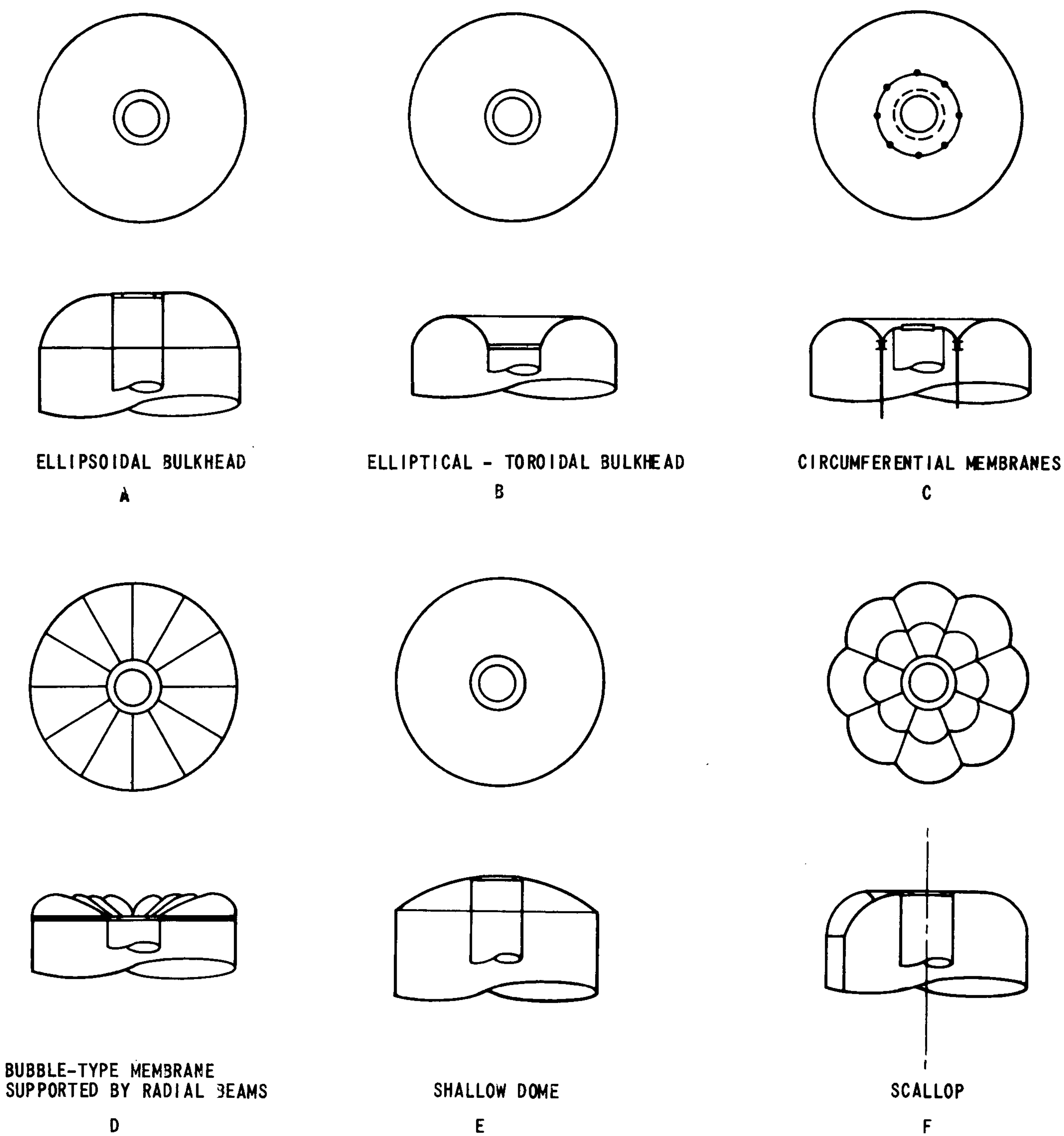
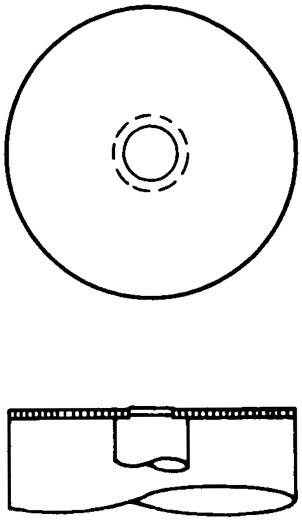
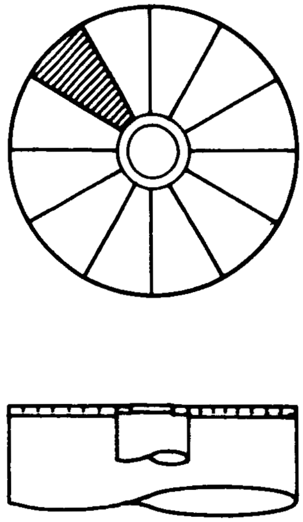


FIGURE 1a - CURVED BULKHEAD CONCEPTS



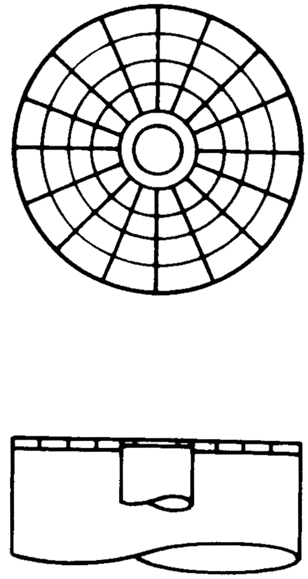
FLAT HONEYCOMB SANDWICH

G



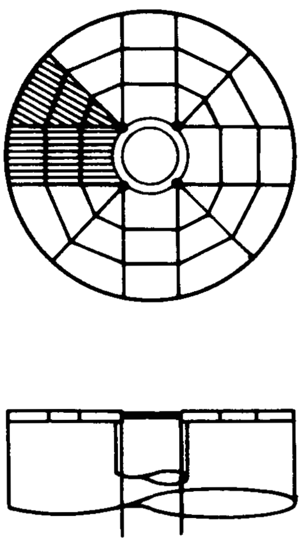
STIFFENED SKIN
SUPPORTED BY RADIAL BEAMS

H



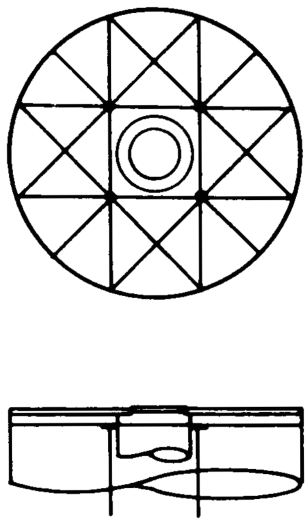
RING STIFFENED SKIN
SUPPORTED BY RADIAL BEAMS

I



STIFFENED
SKIN SUPPORTED BY BEAMS
AND TENSION TIES

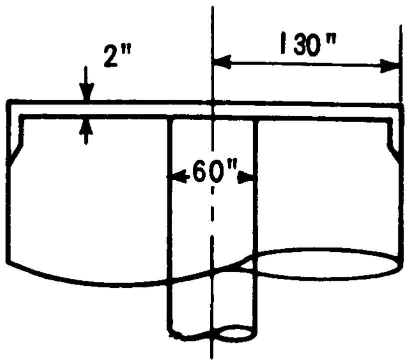
J



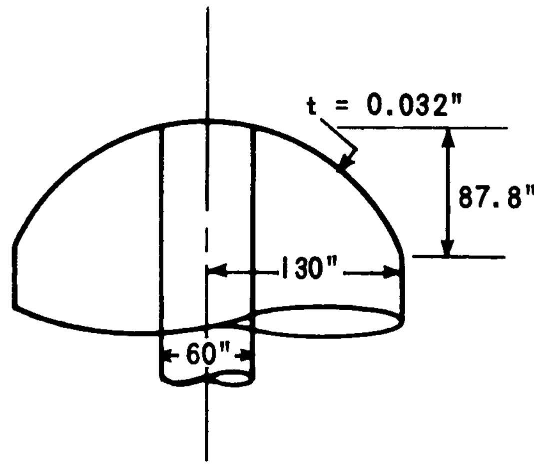
TRIANGULAR SANDWICH PANELS
SUPPORTED BY INTERCONNECTED
BEAMS

K

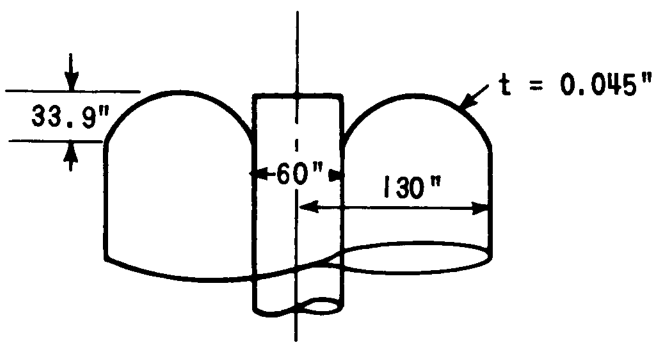
FIGURE 1b - FLAT BULKHEAD CONCEPTS



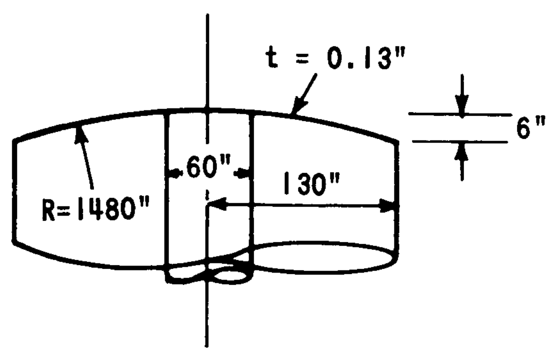
(1) FLAT HONEYCOMB BULKHEAD



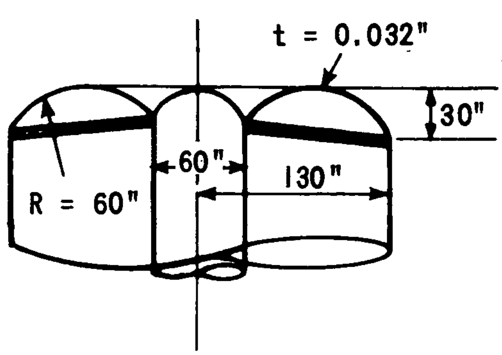
(2) ELLIPTICAL BULKHEAD



(3) MODIFIED SEMI-TOROIDAL BULKHEAD



(4) SHALLOW DOME BULKHEAD



(5) MEMBRANES SUPPORTED BY RADIAL BEAMS BULKHEAD

FIGURE 2 - NAA BULKHEAD CONCEPTS

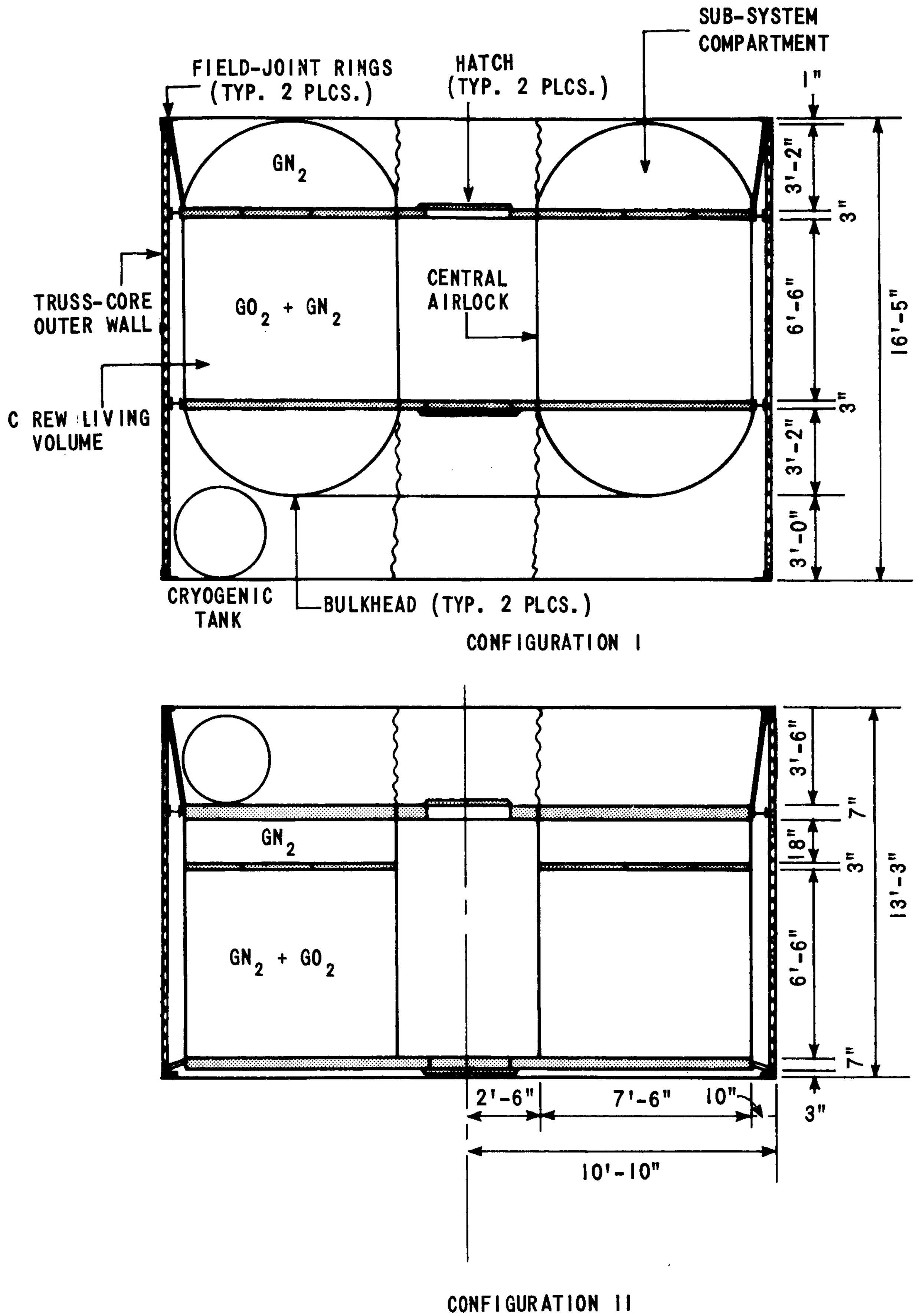
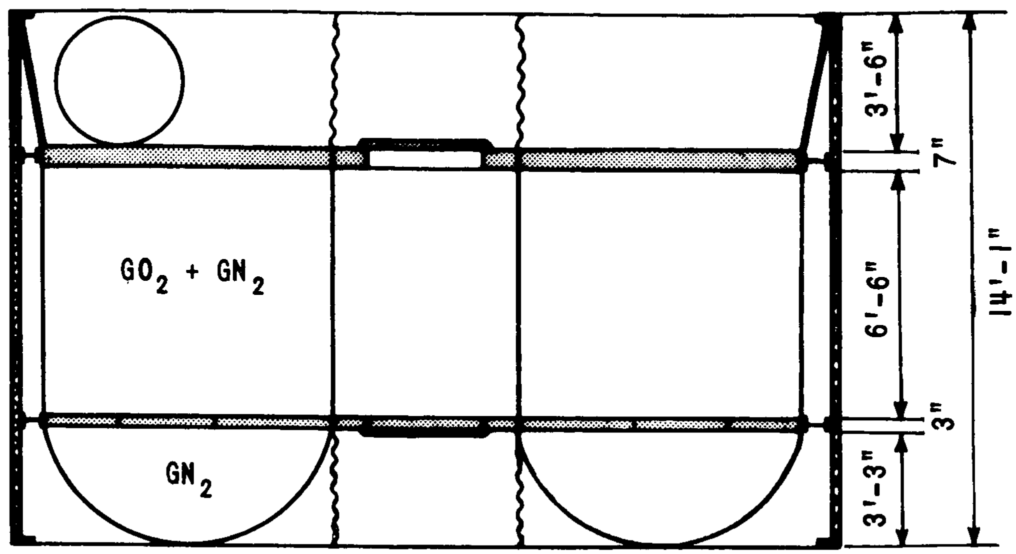
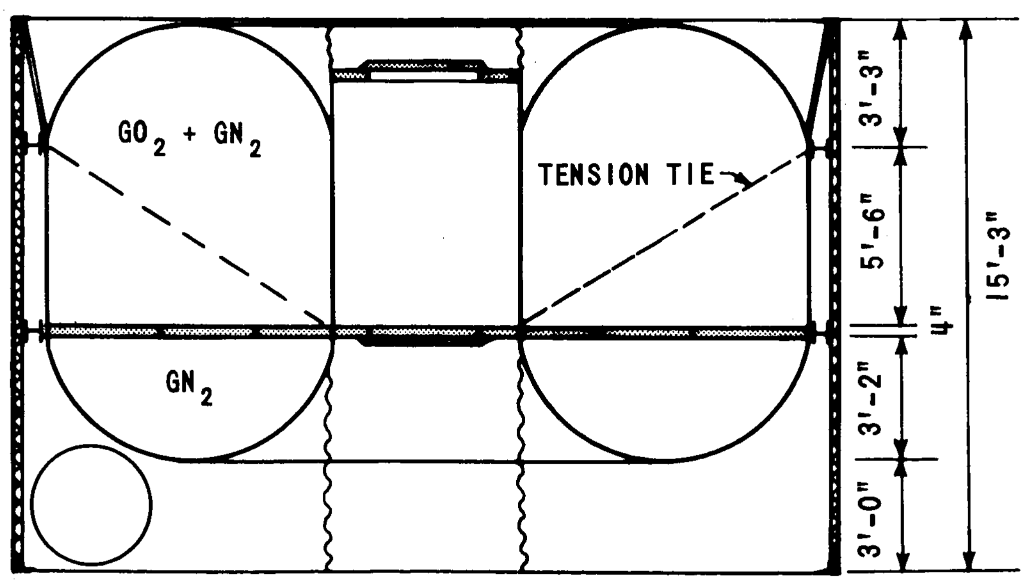


FIGURE 3a - CMM CONFIGURATIONS



CONFIGURATION III



CONFIGURATION IV

FIGURE 3b - CMM CONFIGURATIONS

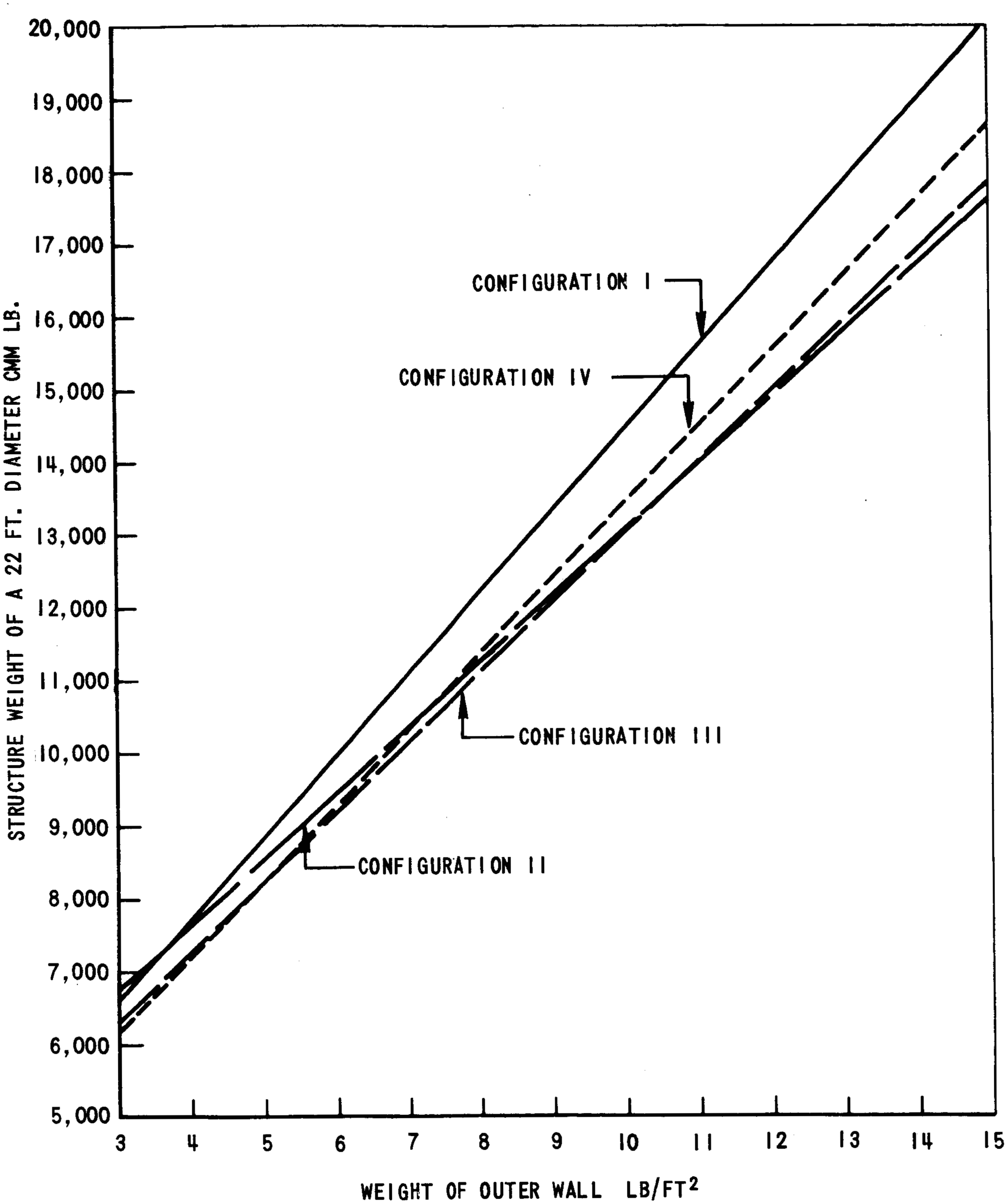


FIGURE 4 - CMM STRUCTURAL WEIGHT

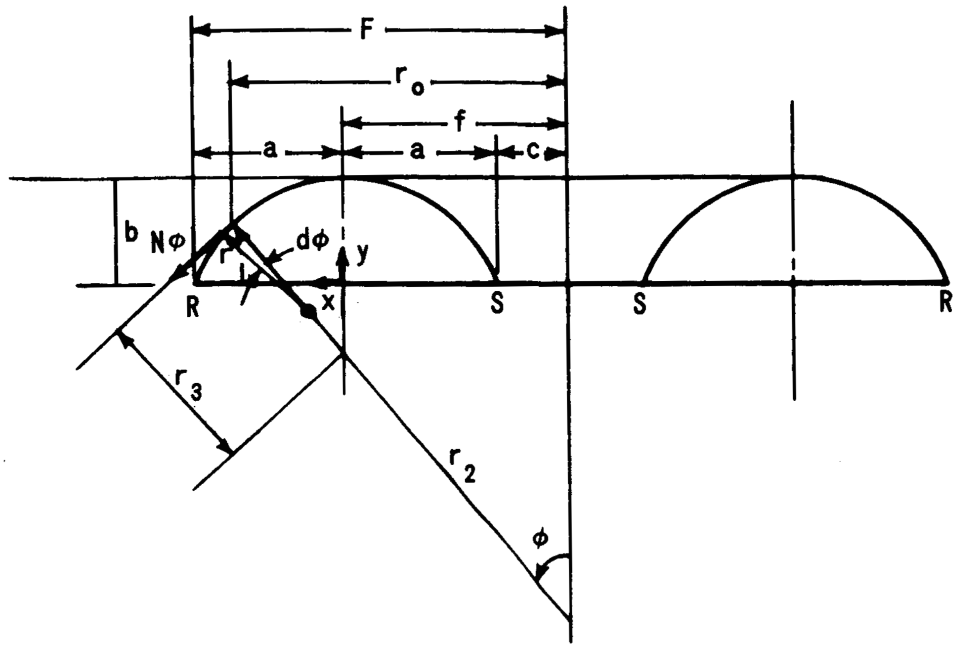


FIGURE A-1 - ELLIPTICAL-TOROIDAL BULKHEAD

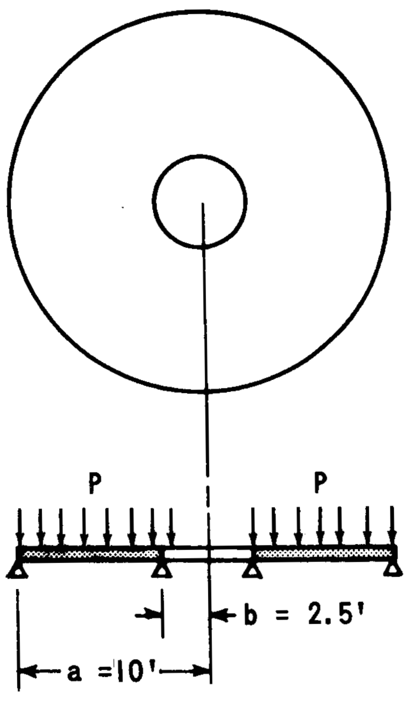


FIGURE A-2 - SIMPLY SUPPORTED CIRCULAR PLATE

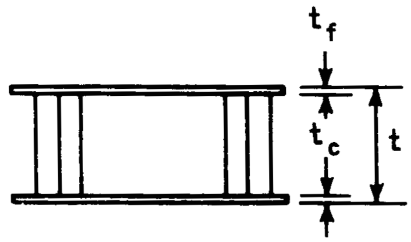


FIGURE A-3 - HONEYCOMB SANDWICH PLATE

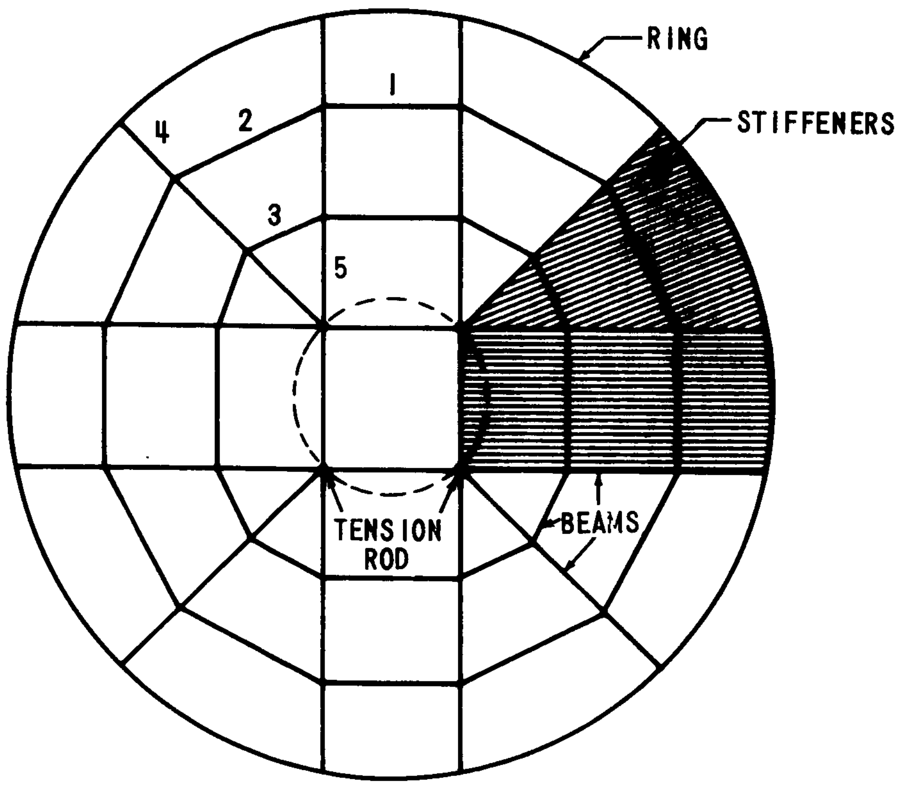


FIGURE A-4 - STIFFENCED SKIN SUPPORTED BY INTERCONNECTED BEAMS

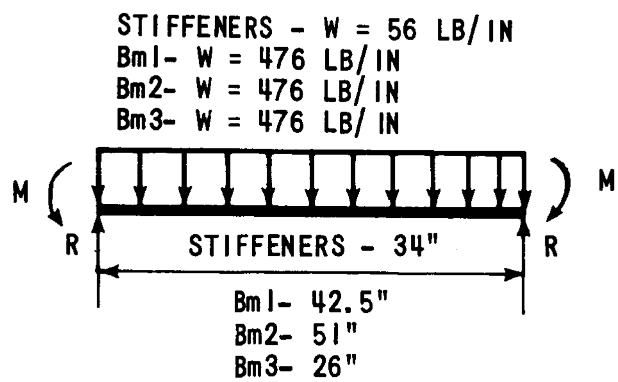


FIGURE A-5 - LOADING ON INTEGRAL FLOOR STIFFENERS

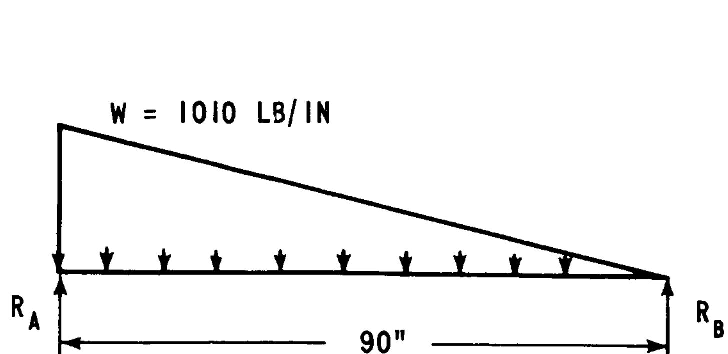


FIGURE A-6 - LOADING ON BEAM 4

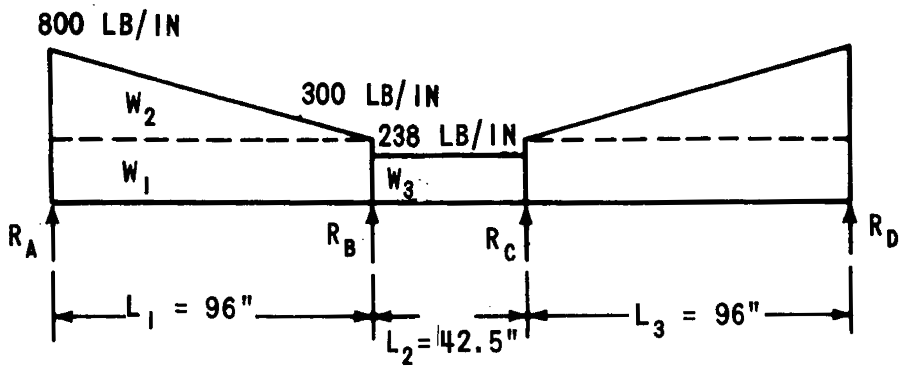


FIGURE A-7 - LOADING ON BEAM 5

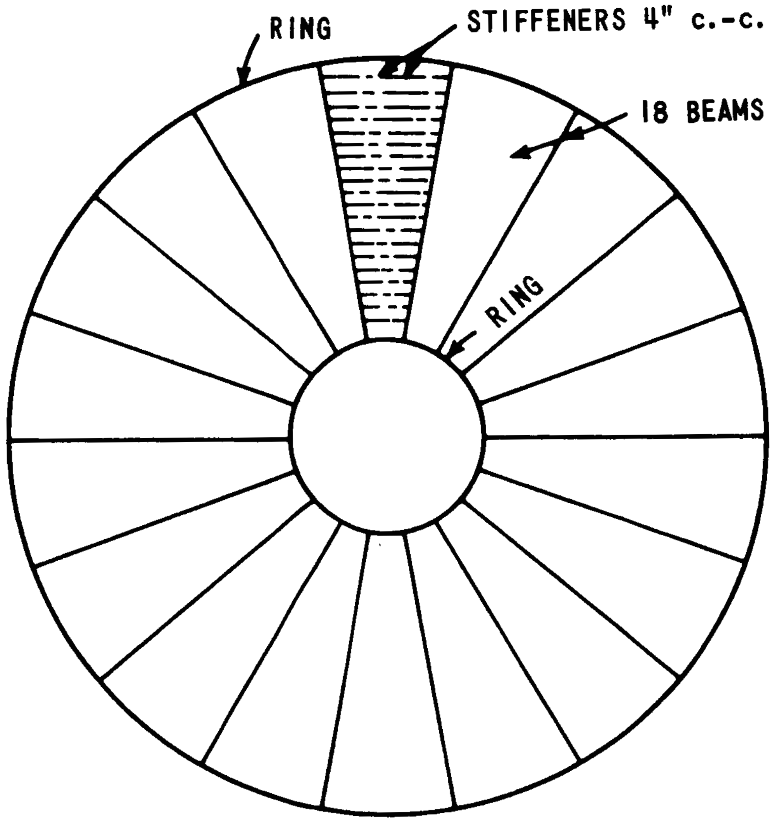


FIGURE A-8 - STIFFENED SKIN SUPPORTED BY RADIAL BEAMS

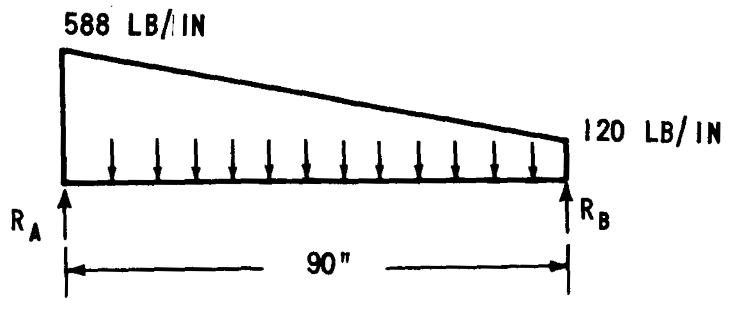


FIGURE A-9 - LOADING ON RADIAL BEAMS

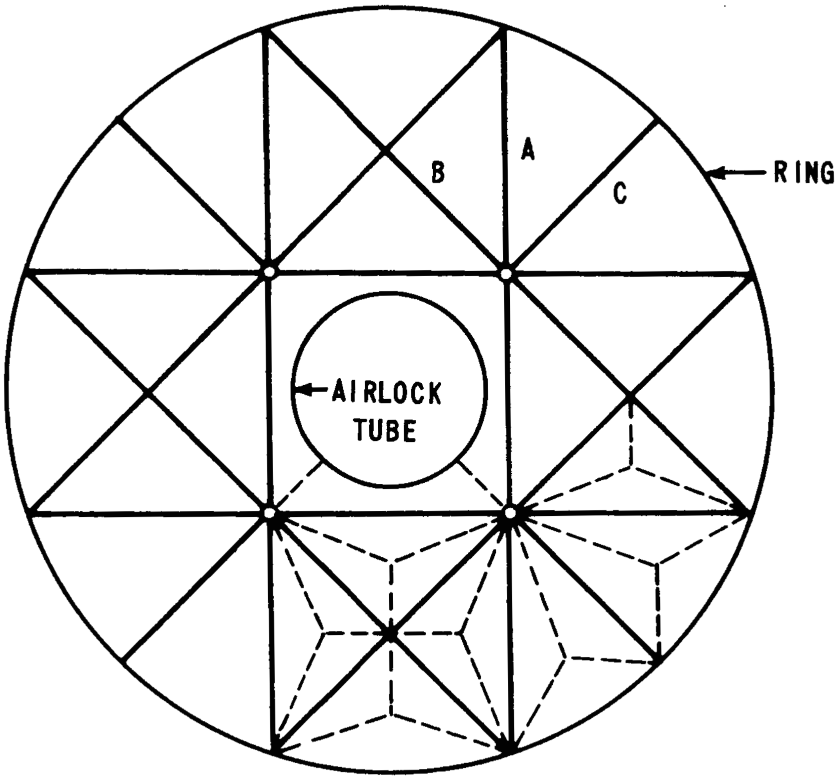


FIGURE A-10 - TRIANGULAR SANDWICH PANELS SUPPORTED BY INTERCONNECTED BEAMS

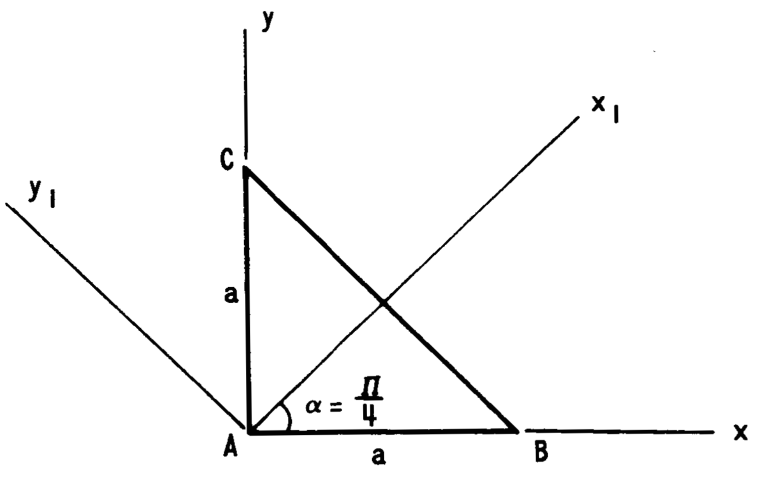


FIGURE A-11 - ISOSCELES RIGHT TRIANGLE PLATE

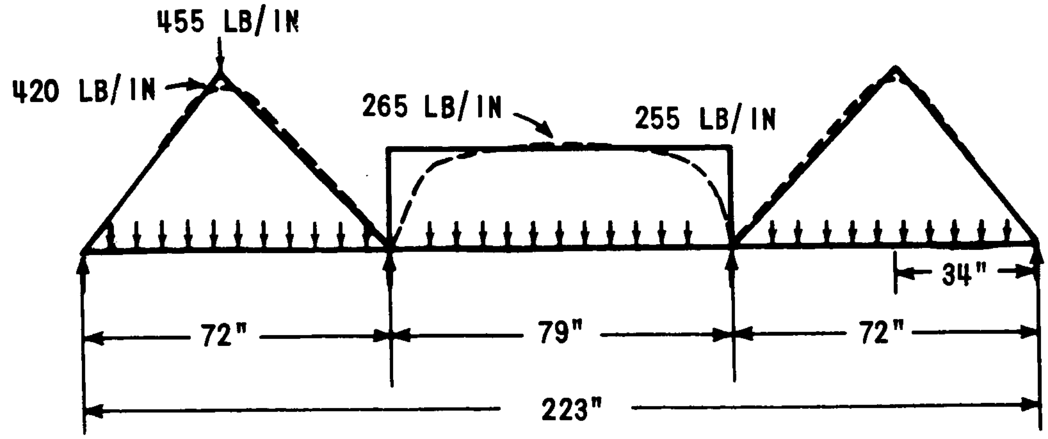


FIGURE A-12 - LOADING ON BEAMS A

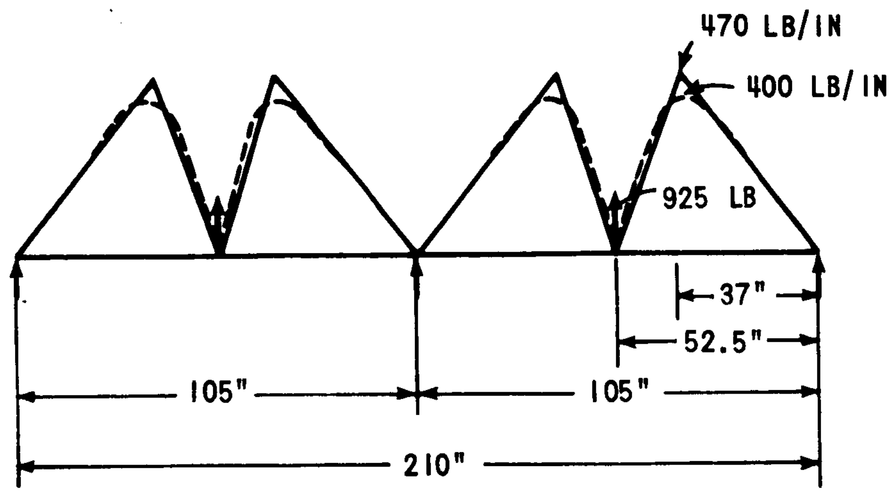


FIGURE A-13 - LOADING ON BEAMS B

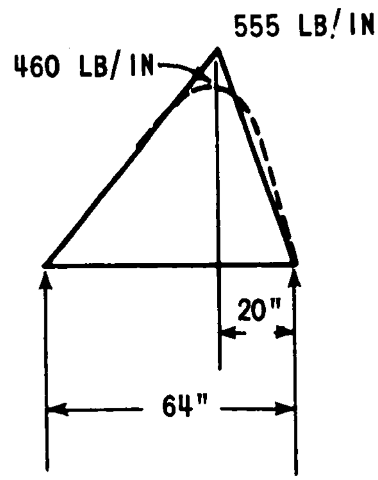


FIGURE A-14 - LOADING ON BEAMS C

BELLCOMM, INC.

Subject: A Study on Bulkhead Configurations for a Common Mission Module
Case 103

From: C. C. Ong

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